Radio Frequency Energy Harvesting for Carbon Monoxide Alarms

by
Mengyuan Guo
B.S. Electrical and Computer Engineering, 2011

Submitted to the
The College of Engineering in fulfillment
of the requirements of
B.S. Honors with Research Distinction in Electrical and Computer Engineering

The Ohio State University
Spring 2011

Table of Contents

Table of Figures

List of Table

1.0 Introduction and Motivation

With increasing awareness in sustainability, electronic wastes are recognized as extremely serious issue today. It is estimated that tens of billions of single-use and rechargeable dry cell batteries are used and then thrown away every year. [1] Recent interest in Green Electronics has triggered the research interest of electronic products not only on low power consumption but also on the design of devices in which the batteries do not get disposed soon.

Such devices would have to rely upon existing natural resources or ambient energy (in some form) to operate, and require some form of circuitry to capture this ambient energy and convert into a DC voltage that can power and run the device, thus the disposal of the batteries is avoided.

A large amount of power is currently being used in the transmission of the electromagnetic waves because of the immense number of communication channels, TV channels, etc. It then makes great sense to take advantage of this existing energy and harvest this power for remote personal applications, like charging a mobile phone or a camera. In addition, the industrial application in the stand-alone devices such as wireless sensor nodes located in hardly accessible places can now work on their own without having human intervention to replace or recharge battery [2]. The recycling of RF energy can significantly cut down the cost when there are many of those devices and making the solution more eco-friendly.

In this project, a carbon monoxide alarm was selected as an application example for radio frequency energy harvesting as it is widely used in any household, however usually installed on the ceiling and is hardly reachable. The ease of having RF energy to power the device is very desirable and useful as the alarm’s battery no longer needs to be replaced. Not only applicable to carbon monoxide alarms, RF energy harvesting is an eco-friendly solution of providing power over distance to many small remote electronic devices which can avoid the dispose of batteries used in them and also lead to the convenience of not plugging into wall for recharging, which shows the wider impact of this project.

2.0 Background

RF energy harvesting has been demonstrated earlier, where in most of the previous RF energy harvesting projects, a dedicated RF source is transmitted for the purpose of harvesting. For example the TX91501 Powercaster™ Transmitter can broadcast radio waves at 915 MHz. In addition, the power transmitted to these antennas is of the order of +10dBm, or 100W, which is quite a large amount of power. The Safety and US Federal Communications Commission also limit the maximum power that can be transmitted this way. While using the transmitters to simulate the RF energy in the ambient, these projects do not contribute to demonstrate the ability of acquiring power directly from the ambient.

Researchers at Intel Seattle Lab was able to power a temperature and humidity meter with antenna placed 4.1m away from TV tower that broadcast 960KW ERP(effective radiated power) as shown in Figure 1. This temperature and humidity meter normally used one 1.5V AAA battery, consume around 25uA at 1.5V from a laboratory power supply, and for every second, the current consumption spiked up to 50uA.

Figure 1 Intel Seattle Lab Experiment

3.0 Problem Statement

Different from the previous RF energy harvesting projects, this project is to investigate the possibility of harvesting ambient RF energy, without adding a transmitter, and to power electronic device at a random location, not close to any transmitter tower. More specifically, this project is to use the ambient energy, the already existing UHF TV radio waves to power carbon monoxide alarm.

3.1 UHF TV Band

Potential bands of interest for RF energy harvesting including FM radio, AM radio, UHF TV and GSM. In terms of channel power, FM radio (87.5-108MHz) has approximately 0.48 dBm (1.1mW) ambient; UHF TV (470-700MHz) has approximately -3.9 dBm (0.41mW) ambient; while for AM radio, the power in strongest few FM stations exceeds the entire AM band, and for GSM, average power per channel is very low at approximately -70 dBm, so AM radio and GSM are eliminated from consideration. Another factor to look at is the efficiency of the antenna at those two bands, in

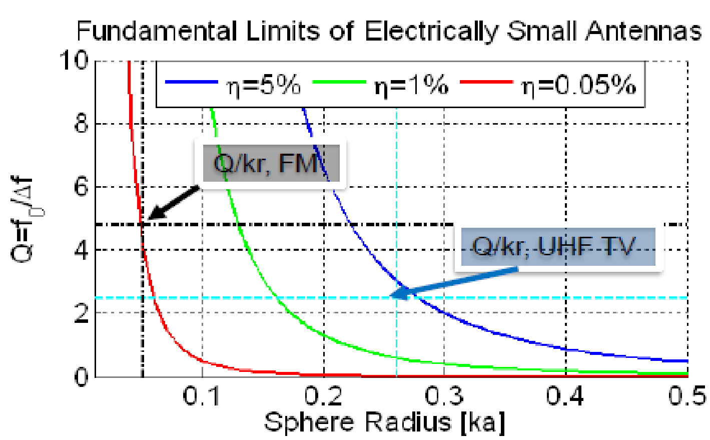

Figure 2 Fundamental Limits of Electrically Small Antennas

accordance to the fundamental limits of antenna as shown in Figure 2, assuming a 2 inch antenna, for UHF TV it has a maximum efficiency of 4-5%, while for FM radio the efficiency is much lower at 0.05%. Thus, based on the channel power and the efficiency, the UHF TV band is more attractive than FM band because it has much higher efficiency with less ambient power.

4.0 Design Process

Ambient energy harvesting is a big structure, and the block diagram illustrating the method being used is shown in Figure 3. Small broadband antenna with good efficiency is used for acquiring the RF energy, and then this low power signal goes to an impedance matching circuit to match the impedance of the rectifier, which is used to convert RF signal into stable DC supply voltage. A super capacitor is to be used between the rectifier and carbon monoxide alarm to store the excess energy.

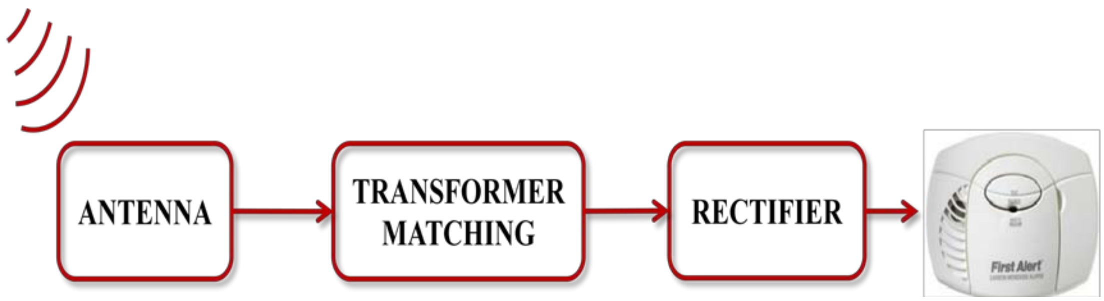

Figure 3 System Block Diagram

4.1 Preliminary Investigation

For this system to work, the basic requirement is that the minimum power needed by the carbon monoxide alarm is smaller than the power that is harvested from the ambient. Thus measurements need to be done to obtain these values: power required by alarm and the ambient power harvested from antenna. The alarm is expected to use minimum power most of time, and use much larger power when it sends out beeps. Under desired condition, the ambient power harvested to be much larger than the minimum required by the alarm, and the extra energy is saved on a super capacitor for use when the alarm needs to beep at which time it consumes much larger power.

4.2 Carbon Monoxide Power Ratings Measurement

First Alert CO400 carbon monoxide alarm was selected for further investigation because it normally use two AA battery (3V total) to power the device as opposed to many alarms that require 9V battery which requires more energy to be harvested. First of all, the operating condition of the carbon monoxide alarm First Alert CO400 was studied. Upon putting two AA batteries, the light flashes and horn sends one beep to indicate that the alarm is powered on. After the sensor has detected enough CO to trigger an alarm, light flashes rapidly and horn sounds loudly (beep once, pause, followed by repeating 4 beeps, pause). This alarm also comes with a testing function, which is used to examine if the device is still at a working condition. The signal it sends out for a successful testing is same as when the sensor detected enough CO, which is light flashes, in synchronization with one beep followed by 4 repeating beeps, pause.

A series of tests were done to measure the operating power of smoke alarm. Power is the product of voltage multiplied by current. There are two power of interest, peak power when the carbon monoxide alarm's horn is beeping which sinks a large current, and the idle power at the majority of time when the current is low.

First, to get the minimum voltage required to power on the CO alarm, the method used was to connect the power supply Agilent E3620A 0-25V, 0-1A, in series with the alarm. Voltage supplied to the circuit from the power supply was gradually increased until the first beep was heard which means the alarm is powered on. This number measured to be 1.92 V with the digital multimeter Fluke 8010A. This number thus provides the V in the calculation of power P=V*I.

Next, the current circulating in the CO alarm needed to be investigated. The simplest way to measure the current would be to connect the digital multimeter in series with the alarm circuit. However since the current is not constant, it was hard to keep record of how the current change as time varies. Thus the digital oscilloscope HP infinium 500MHz 1GSa/s was employed to acquire the instant data. It can only measure the instant voltage, with the known resistance value, instant current is equal to voltage divided by resistance (I=V/R). A resistor of 1.1 ohm was connected in series with the power supply and CO alarm. The probes of the oscilloscope were placed across the resistor. The setup is shown in Figure 4:

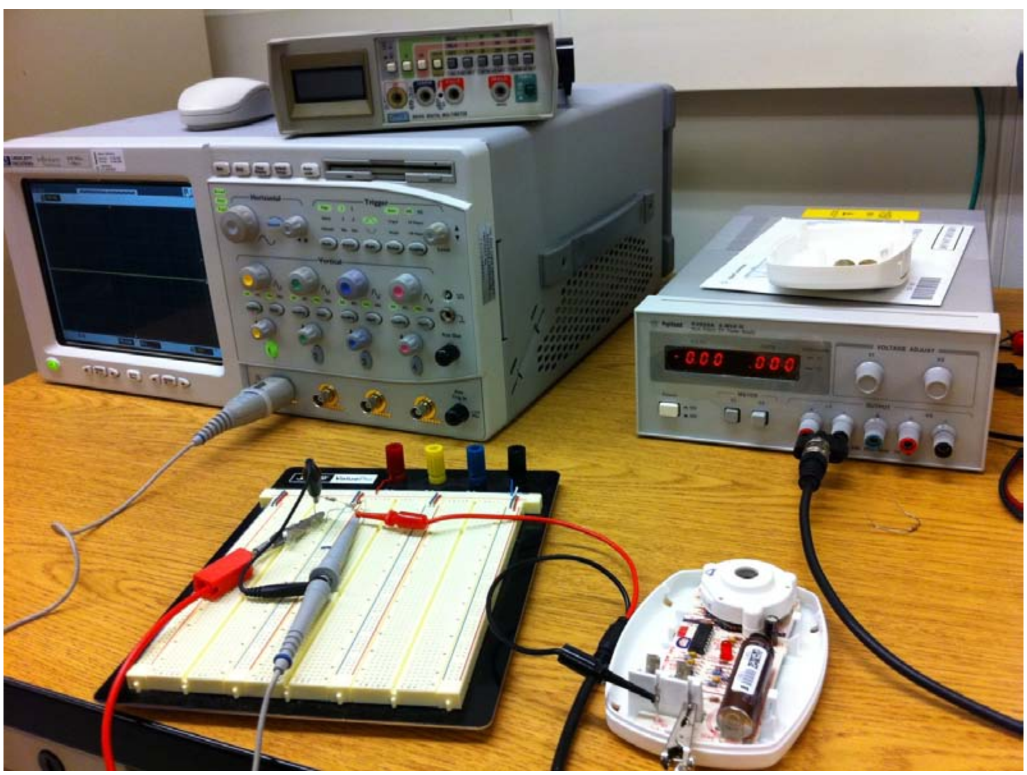

Figure 4 Carbon Monoxide Alarm Power Measurement Setup

It is found out that during the test that the power supply needs to provide 2.12V for the alarm to signal that it’s powered on. The resolution selected for oscilloscope is

500ms/div, and 250 samples per seconds which is just enough to capture the one horn pattern: one beep, paused followed by four repeating beeps. The resulting current versus time graph is shown below in figure 4.2.2

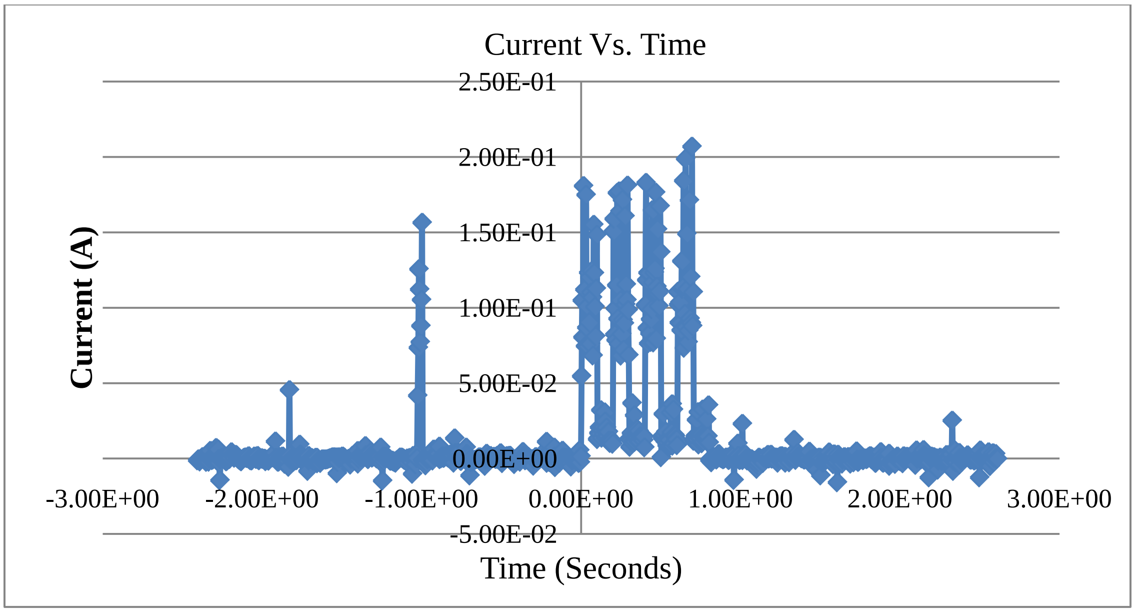

Figure 5 Instant Current vs. Time

From this figure, it can be seen that the peak current (when the alarm beeps) is very much larger compared to the idle current. Thus there are two different currents of interest here. The idle current gives the information of the minimum power consumed by the CO alarm, which is calculated from minimum voltage required multiplied by the idle current. The peak current gives the information of the peak power as well as the energy required to sustain one repeating four beeps. To get a more accurate average peak current or idle current, individual tests need to be done with higher resolution settings on the oscilloscope. Thus, another test was done with oscilloscope set to 20ms/div time resolution to measure the current only during one beep and the result is shown in the Figure 6 below.

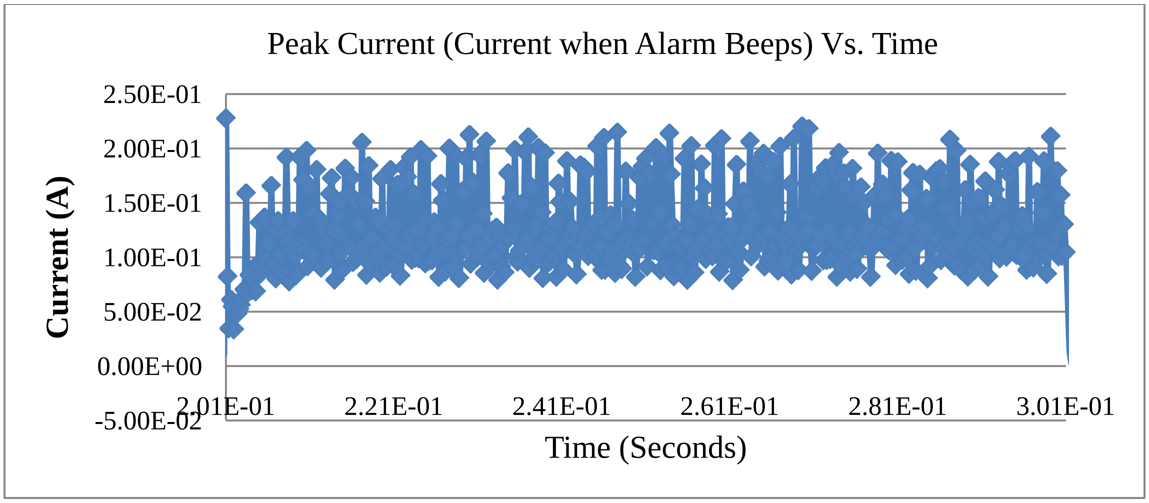

Figure 6 Instant Peak Current vs. Time

By doing integration over the range of one beep of 100ms, which is just taking the average of the values since each data points are taken at the same interval of time, the average peak current is found out to be 0.146 amperes. This means that the energy required for a repeating four beeps for the CO alarm is 1.92V*0.146A*100ms*4=0.112J.

Referring back to the overall current versus time graph, the idle current was fluctuating around zero. After a few of the same measurements tested with this 1.1 ohm resistor and a 12 ohm resistor, it is realized that the measured voltages drops below zero sometime is due to the fact that the values being measured drop below the noise floor of the oscilloscope, which is 10mV. However, if it were just to change to a large enough resistor, it would require a large voltage to power this circuit (CO alarm, in series with power supply, and a resistor) on. With a 12 ohm resistor, it would require a 3.7V from power supply to power the alarm on, but still the voltage across the resistor was measured to be below zero at times. For a large resistor, it needs larger voltage, which could exceed the maximum voltage of 25V that can be provided by the power supply and it was also a concern that this could damage the CO alarm.

Thus another method needs to be employed to obtain the idle current. It is then attempted to parallel a 1.1 ohm resistor and a 100k ohm resistor, connected in series with power supply and CO alarm with the oscilloscope measuring the voltage across the resistors. A time resolution of 1 ms/div was used for the oscilloscope. The voltage was increased to 2.03 V when the CO alarm beeps to indicate that it's powered on. Then the 1.1 ohm resistor was removed from the circuit and leaving only 100k ohm resistor connected in the circuit. This way the voltage the oscilloscope is measuring is large enough to overcome the noise floor. The resulted current versus time graph is shown in Figure 7.

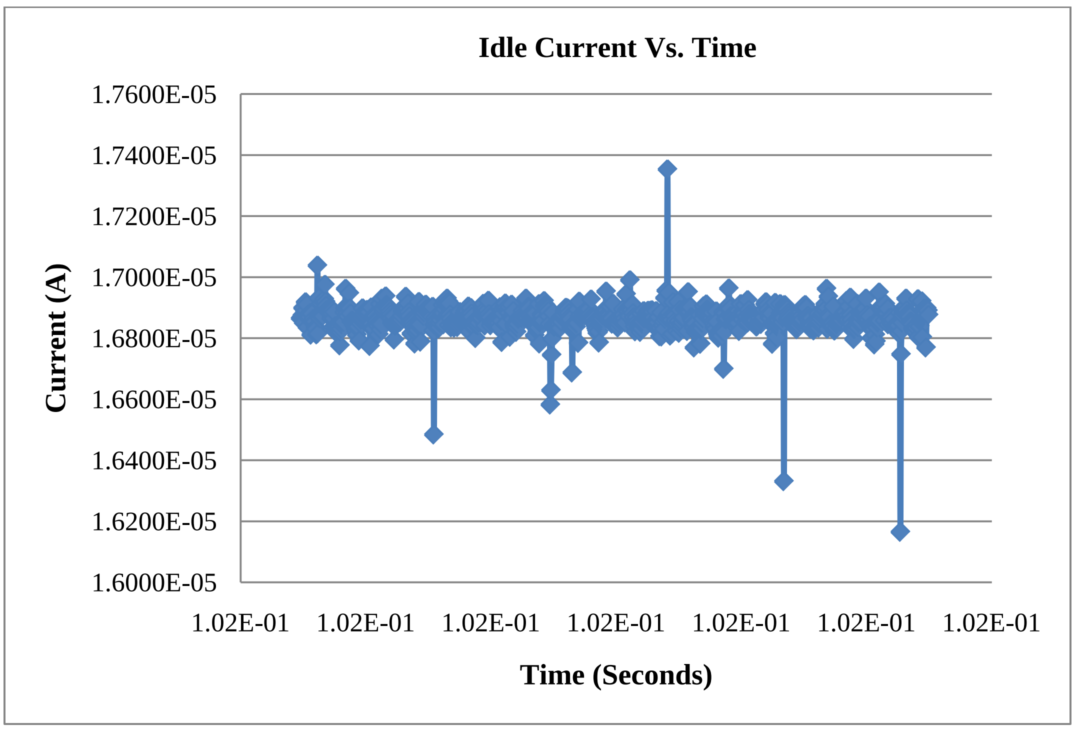

Figure 7 Instant Idle Current vs. Time

By the same method as used to get peak current, the average idle current is calculated to be 16.86 micro amperes. Thus the power consumed during idle state is 1.92V*0.00001686= 32.4 micro watts. There is no meaning to calculate the energy consumed since the CO alarm is meant to be kept at idle state forever. This idle state power is also the minimum power required by the CO alarm.

4.3 Ambient Power Measurements

Horn antenna, with a wide operating bandwidth from 0.5 GHz to 6GHz, and UHF TV chip antenna which is dedicated for UHF TV band (470MHz-860MHz) were used to acquire the ambient power and both underwent various tests to ensure more accurate results.

4.3.1 Ambient Power Measurements with Horn Antenna

Originally, the horn antenna AEL 1734 (shown in Figure 8) was used as this antenna has a good gain profile which was then expected to acquire the most ambient power. The gain of this horn antenna was measured in the Electroscience Laboratory's chamber as listed in the Table 1 for the frequencies of interest (UHF TV band). The gain is positive throughout 470-680MHz.

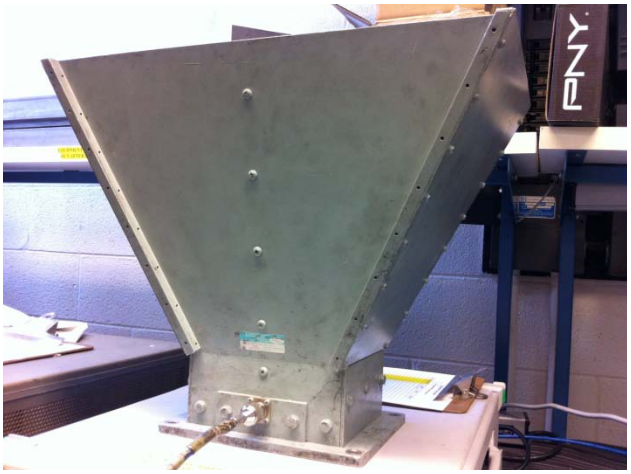

Figure 8 Horn Antenna

Frequency (MHz)	Gain (dB)
450	5.94
475	6.369
500	6.409
600	6.002
700	7.696

Table 1 Horn Antenna Gain

Both outdoor and indoor measurements were conducted in Electroscience Laboratory (1320 Kinnear Road, Columbus, OH 43212). The peak channel power across 470MHz-680MHz was measured to be -30dBm although on rainy days the channel power measured was as low as -46dBm. This number fluctuates as the orientation of the antenna changes but no significant difference was found between the measurement results of the outdoor or indoor measurements. Since -30dBm is 1 micro watt, which is less than the minimum power required by the CO alarm of 32.4 micro watts; the power acquired is not enough to supply the alarm.

The website www.tvfool.com provides the list of stations that has the best signals at the measurement location. On a rainy day when the total channel power was found to be -46 dBm, the channel power for each station was measured indoor with the horn antenna and compared to the given information about the signal analysis found on the website, as shown in Table 2. For example, for NBC station which is transmitting power at 83.3 dB at 2.1 miles away, should have -7.5 strength of power from the measurement location. However, the measured power for this station (channel power at 470-476 MHz) is -50.23 dBm. Moreover, there should be a significant drop of power that can be received at this location from channel WCMH-DT all the way down to WSFJ-DT as listed on the table according to that website, but this was not proved by the actual measurements done indoor. In general, the measurement results showed a small drop of power received as it goes down from the list.

Channel Name	Channel Number	Frequency (MHz)	Networks	NM(dB)	Pwr(dBm)	Dist (Miles)	Actual Power Measured (dBm)
WCMH-DT	12	470-476	NBC	83.3	-7.5	2.1	-50.23
WBNS-DT	21	512-518	CBS	83.3	-7.9	2.1	-54.5
WTTE-DT	36	602-608	FOX	75.7	-15.2	4.4	-50.5
WSYX	48	674-680	ABC	74.7	-16.2	4.4	-48.14
WDEM-CD	17	488-494		64.2	-26.7	2.1	-60.87
WOSU-DT	38	614-620	PBS	63	-27.8	12.8	-58.17
WCLL-CA	19	500-506		60.9	-30	2.1	-55.61
WSFJ-DT	24	530-536	Ind	54.8	-36	19.3	-58.5

Table 2 List of Channel Power Measured with Horn Antenna for Each Station

Therefore, the measurements with the horn antenna did not provide desirable results, and from the comparison which showed that the power acquired did not have a significant decline as it was supposed to, it is concluded that a different antenna needed to be used to acquire more power from the ambient UHF TV band.

4.3.2 Ambient Power Measurements with UHF TV Chip Antenna

Since this antenna will be placed in a CO alarm, antenna that is small in size is desired. Moreover, antenna that is designed specifically for UHF bandwidth is being expected to have better performance compared to the horn antenna used that has a operating frequency range from 0.5GHz to 6GHz. Many high gain UHF antennas are big and thus not applicable for this purpose. There are two small UHF chip antennas found that satisfies the requirements. Their gain data are similar thus the one chosen was the one that's relatively smaller in size. This Vishay RFW8022 has a small outline of 35mm length, 5mm width and 1.2mm thickness. It is to be used for frequencies 470MHz-

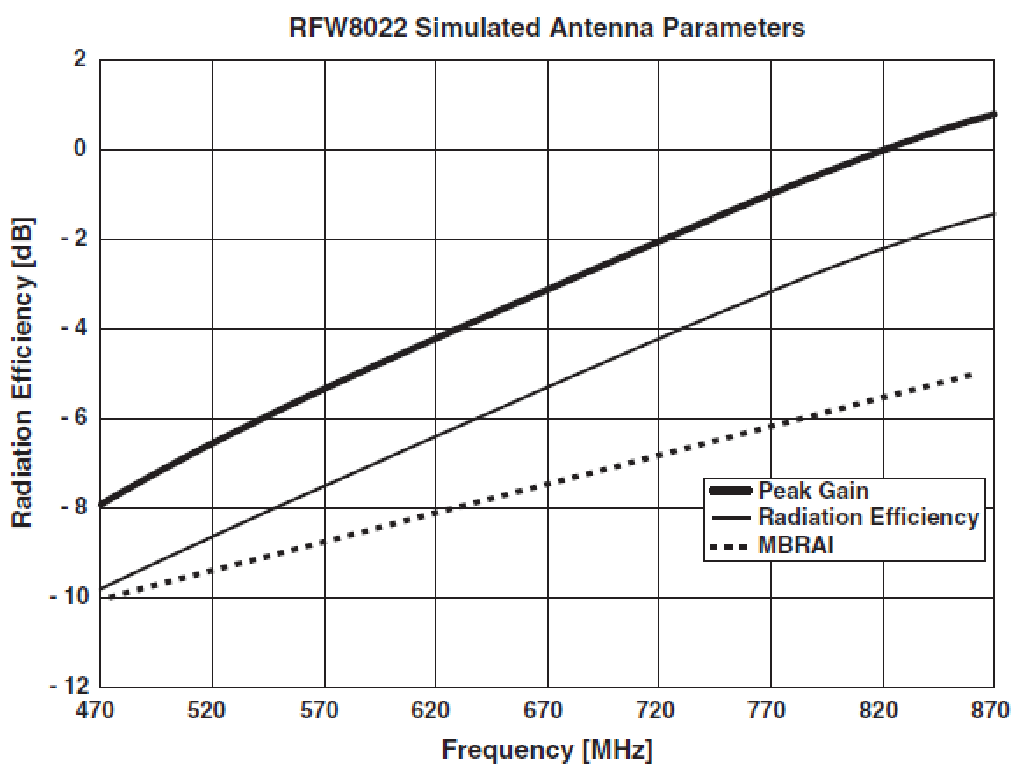

Figure 9 UHF TV Chip Antenna Gain

860MHz. Figure 9 was obtained from the manufacturer datasheet, which shows that this antenna has a gain of -8 to -3dB in 470MHz-680MHz. This is worse compared to the positive gain of the horn antenna that was used, but since this antenna has a smaller bandwidth, it is of interest to see if it can acquire more power.

This antenna bought was mounted to circuit board according to the assembly instruction on the datasheet. The ground plane design used the one shown on the datasheet while the feed line was designed in accordance to Microwaves101 website. Given the dielectric constant of the board used which is 6.6, the thickness of the substrate which is 50 mils, the width of the feed line needs to 0.0695 inches to match the impedance of 50ohm of the antenna. The front and back of the board were designed and drawn in Ansoft HFFS and were then fabricated using LPKF ProtoMatS62 Circuit Board Plotter. An SMA connecter was also soldered onto the end of the feed line. The completed board with antenna mounted is shown in figure 10 for a front view of the board.

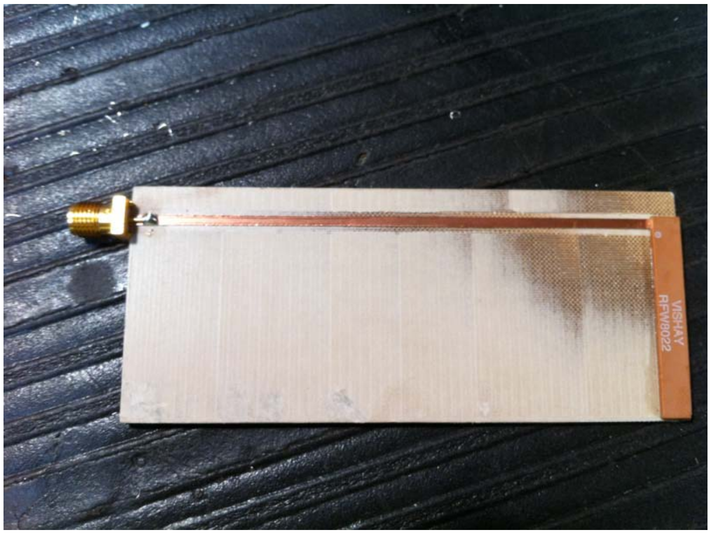

Figure 10 Front View of the Board with Antenna Mounted

The performance of this antenna was then assessed with a network analyzer and Figure 11 shows the result.

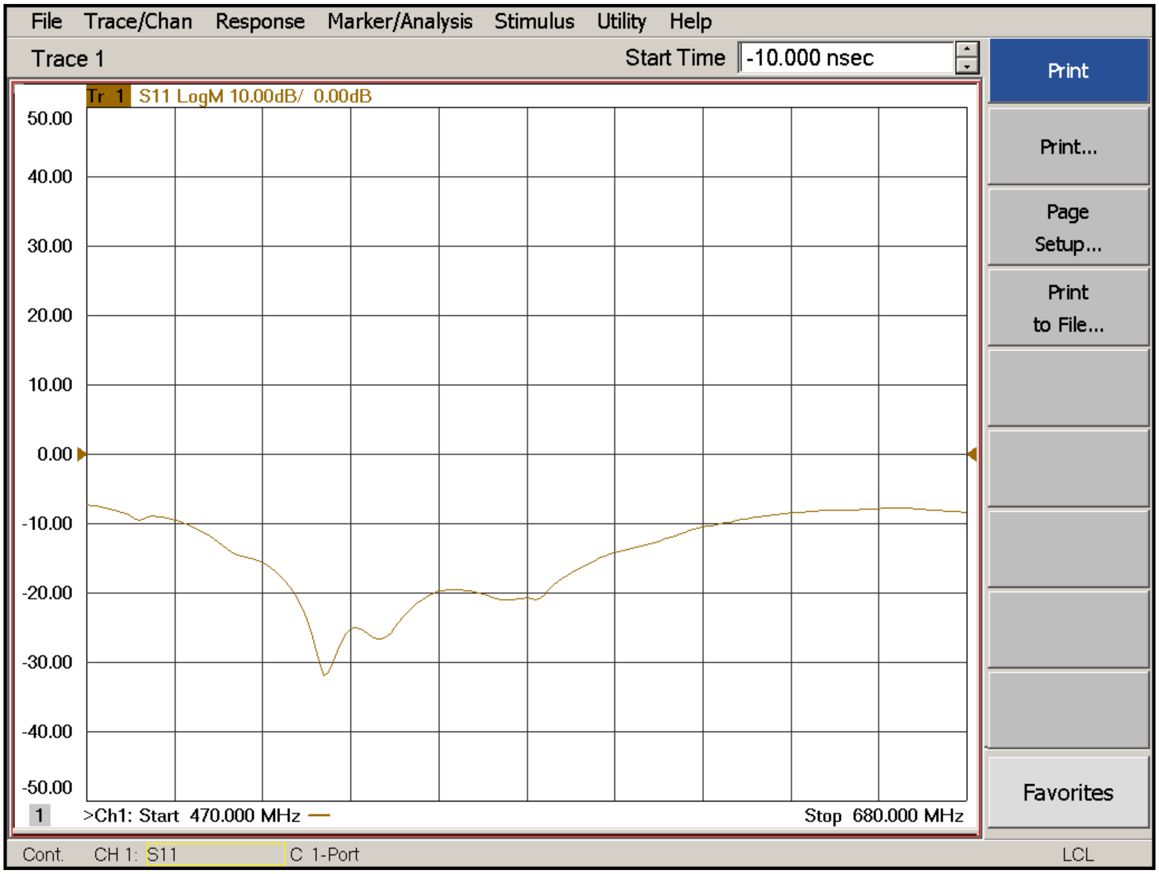

Figure 11 Horn Antenna Assessment with Network Analyzer

The network analyzer plotted the attenuations for 470-680MHz. The antenna has approximately better than -10dB return loss over the entire band.

First ambient power measurement with this UHF chip antenna was done indoor also in room 161 of Electroscience Laboratory and the channel power from 470MHz to 680MHz was measured to be -46dBm only. This result is much worse compared to what the horn antenna measured. Thus, another measurement was proposed to be done with this chip antenna outdoor on top of the roof of this two floor building. The channel power from the same 470-680MHz was measured to be -31dBm, which is significantly better than the indoor measurements. This is, still however, significantly worse compared to the data as given on tvfool website, which advised that a total power of 7.5dBm could be received. To investigate more into this, small interval channel power measurements were made to compare with the specific channel power for each TV station listed on the website and Table 3 shows the result found. For each channel, the actual power measured were much smaller than the power indicated on the website, for example, NBC, transmitting power 2.1 miles away from the laboratory, supposed to receive -7.5 dBm of power, was actually acquired of -38 dBm power with Vishay RFW8022.

Channel Name	Frequency (MHz)	Networks	Power (dBm)	Dist (Miles)	Actual Peak Power Measured (dBm)
WCMH-DT	470-476	NBC	-7.5	2.1	-38
WBNS-DT	512-518	CBS	-7.9	2.1	-35
WTTE-DT	602-608	FOX	-15.2	4.4	-38
WSYX	674-680	ABC	-16.2	4.4	-37
WDEM-CD	488-494		-26.7	2.1	-59
WOSU-DT	614-620	PBS	-27.8	12.8	-56
WCLL-CA	500-506		-30	2.1	-49
WSFJ-DT	530-536	Ind	-36	19.3	-59

Table 3 List of Channel Power Measured with UHF Antenna for Each Station

4.4 Rectifier Design

A Greinacher Rectifier is used and shown below in Figure 12 is the design in Advanced Design Systems (ADS). Term1 is the antenna, which has 50 ohm impedance. Term2 is to simulate the carbon monoxide alarm, which has an idle state impedance of 1.92V/16.86 mA=113879 ohms. The capacitances of C3 and C4 are 100uF to lower leakage loss. The capacitances of C5 and C6 as shown in the diagram need to be calculated from equation W=1/2*C*V^2, and the W is the energy they need to store in them. This rectifier design is not completed because the measurements done before did not give satisfactory results as how much energy can be harvested. The simulation result, though, shows that an impedance matching circuit is necessary because the impedance of the rectifier circuit is not at 50 ohms.

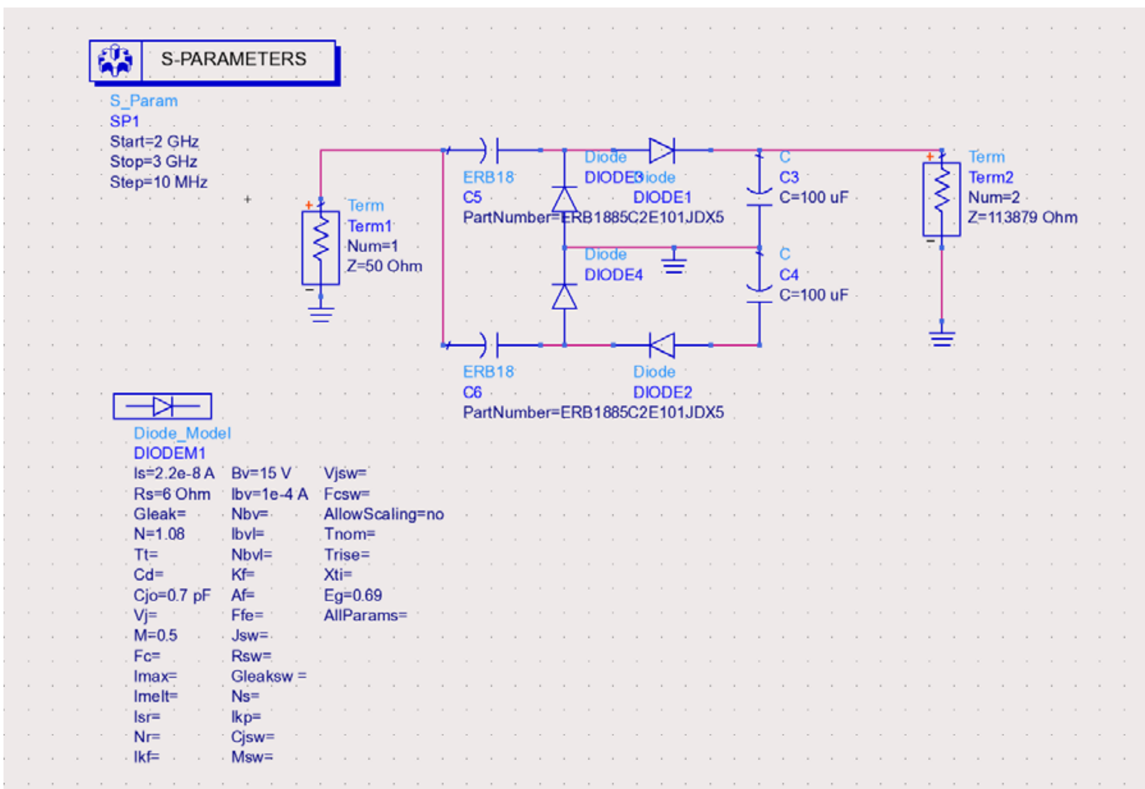

Figure 12 Rectifier Design

5.0 Summary and Conclusions

The minimum power required by the carbon monoxide alarm was measured to be 32.4 uW. The peak power that can be harvested with the UHF chip antenna is -31dB which translates to 0.79 uW, which is about 50 times smaller than the required 32.4 uW of the alarm. These results show how small ambient power is and how small it is even compared to the power required by the small home electronic devices which is the reason that RF energy has not been a feasible option as an alternative energy source yet. From what this research has shown so far, with the amount energy the horn antenna or UHF TV antenna can receive, it is not enough to power the CO Alarm.

5.1 Contributions

Through this project, I obtained the ratings of CO alarm which are not readily available and showed how large of power it actually require, in contrast to many people's assumption that it only used very little power. The problem is not that it requires 3V of voltage, but that it consumes a large current. I also showed through my ambient measurement results that for UHF TV antenna, it performs much better in the broadly open space as opposed to it does inside. Thus the more realistic application of using RF power is for mobile electronics that's used in an open air environment, not something that's being used in a house like a carbon monoxide alarm. Cell phones, cameras are examples of more suitable applications. Lastly, I showed the differences of the amount of UHF TV power that can actually be harvested with a chip antenna as opposed to the standards. And the power that can be acquired is much smaller.

5.2 Future Work

To get more desirable results, future work needs to be implemented as discussed below. Multiple antennas can be used to acquire power together, and the combine power is possible to be enough to supply the end application. This will sacrifice the area constraint as more antennas will take up more space, but with the chip antenna this small compared to a mobile phone, for example, multiple of them could fit into a mobile phone easily. Moreover, better UHF TV antennas need to be designed without increasing the size. Lastly, another way to get this system to work with the ambient power I was able to acquire using the UHF TV antenna, is to find a mobile electronics that use as little as -30 dBm of power.

Acknowledgements

I would like to express my sincere appreciation to Prof. Waleed Khalil for serving as the advisor for an academic year and provided much guidance for me on this project. Thanks to Prof. Patrick Roblin for providing lab equipment for the carbon monoxide power ratings measurements. They also both attended my oral thesis defense and we had a good discussion. Moreover, graduate student Ugur Oglun helped and provided suggestions on antenna build. Another graduate student, Haedong Jang helped me with the oscilloscope used in carbon monoxide power ratings measurements. The College of Engineering also provided support by giving me scholarship for the duration of the research project.

BIBILOGRAPHY

[1] Chris Caroll, “High-Tech Trash,” *National Geographic Magazine*, Jan 2008

[2] T.M. Chiam, et. al, “5.8 GHz Circularly Polarized Rectennas Using Schottky Diode and LTC5535 Rectifier for RF Energy Harvesting.” *2009 Asia Pacific Microwave Conference*, pp. 32-35, 2009

[3] R.C. Hansen, “Fundamental Limitations in Antennas,” *Proceedings of the IEEE*, vol. 69, issue 2, pp. 170-182, 1982

[4] J. A. Hagerty, et. al, “Recycling ambient microwave energy with broadband rectenna arrays.” *IEEE Trans. On MTT*, vol. 52., no. 3, pp. 1014-1024 March 2004

[5] D. Harrist, “Wireless Battery Charging Systems Using Radio Frequency Energy Harvesting”, University of Pittsburgh 2004, p. 5, 2001

[6] P. Li et el “A low power battery management system for rechargeable wireless implantable electronics,” *ISCAS 2006*

[7] S. Mandal, et. al, “A Low-Power, Battery-Free Tag for Body Sensor Networks.” *IEEE Pervasive Computing*, vol. 9, issue 1, pp. 71-77, 2010

[8] U.Olgun, “Investigation of Rectenna Array Configurations for Enhanced RF Power Harvesting”, 2011

[9] A. Sample, “Experimental Results with two Wireless Power Transfer Systems” Intel Research Seattle, p. 3, 2009